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ROTORCRAFT SIMULATION FIDELITY IMPROVEMENTS THROUGH AUGMENTED ROTOR INFLOW

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Abstract
In rotorcraft research, the prediction of correct off-axis response using a simulation model is a challenging task, particularly for hover and low-speed flight. This can be attributed to the complex aeromechanical behaviour exhibited by a rotorcraft, including the unsteady and hysteretic nature of the main rotor wake and its coupling with the fuselage and empennage in manoeuvring flight. A traditional approach to improve the off-axis response prediction is to include the manoeuvre wake distortion effect arising from the variation of the induced inflow through the rotor disc. Various approaches have been developed to deal with this phenomenon but usually demand prerequisites of high levels of expertise and profound aerodynamic knowledge. This paper presents a new and practical approach to capturing this wake distortion through an augmented rotor inflow model. The proposed model is integrated into a nonlinear simulation using the FLIGHTLAB environment. The response comparisons between the simulation and flight test in hover indicate the good quality of the proposed model. The results reported are part of ongoing research at Liverpool and its partner Institutions into rotorcraft simulation fidelity for predicting dynamic behaviour for operationally-relevant mission-task-elements.

NOTATION

C_L, C_M, C_T	coefficients of aerodynamic roll, pitch and thrust moment perturbations
K_{pc}, K_{qc} etc.	inflow augmentation coefficients [n/d]
$[L]$	aerodynamic influence coefficient matrix
N_b	number of blades of main rotor [n/d]
p, q, r	angular velocity components of helicopter about fuselage x-, y-, z-axes [deg/s, rad/s]
R	rotor radius [ft]
v_0, v_{1c}, v_{1s}	induced velocities components [ft/s]
$\bar{V}$	mass-inflow parameter
X_a, X_b	pilot lateral and longitudinal cyclic stick inputs [inch]
X_c, X_p	pilot collective and pedal inputs [inch]
X	wake skew parameter $= \tan(\chi/2)$ [n/d]
χ	wake skew angle $= \tan^{-1}(\mu/\lambda_0)$ [deg, rad]
Ω	main rotor speed [rad/s]
λ_0, λ_{1c}, λ_{1s}	rotor uniform and first harmonic inflow velocities (normalized by ΩR) [n/d]

1. INTRODUCTION

The ability to replicate the real flight behaviour in a realistic environment is the key ingredient of good flight simulation, in which pilots can be trained to safely operate the aircraft. This requires the simulation models to possess sufficient fidelity to predict the flight responses within reasonable tolerances. One of the challenges in the field of rotorcraft modelling is the prediction of the correct off-axis responses [1-3], e.g. pitch from roll, yaw from collective. The discrepancies between flight and simulation can be attributed to main rotor wake effects and also interaction/interference effects on the fuselage, empennage and tail rotor. The Pitt and Peters finite-state dynamic wake model [4] has been extensively used to model the helicopter main rotor wake and provides an approximate representation of the induced inflow components in the state-space form. Takahashi [1] used the Pitt and Peters dynamic inflow model for predicting the rotor inflow of the UH-60 Blackhawk helicopter in hover, predicting off-axis response to cyclic inputs with opposite sign compared with flight. This was attributed to the assumption of an undistorted cylindrical rotor wake geometry, that does not incorporate the wake distortion effects due to the rotation of the rotor tip-path-plane resulting from the application of cyclic controls in manoeuvring flight.

The rolling or pitching rotor in manoeuvring flight results in the rotor wake effectively being compressed on one side and expanded on the other side, leading to differential changes in the induced velocities through the rotor disc. These so-called manoeuvre wake distortion (MWD) effects are seen as the potential candidates to improve the off-axis response predictions [5-9], mainly at low-speed flight conditions; with increasing speed the wake is swept backward resulting in increased downwash at the rear, relative to the front, of the rotor disc. Basset [8] performed a parametric study of the variation of inflow gradients with forward speed, showing that the longitudinal coefficient in MWD changes sign with increasing forward speed. The existing approaches to modelling rotor wake, and their distortion effects, are based on modifications applied to dynamic inflow equations. Therefore, extending these approaches to new helicopter configurations requires prior knowledge of wake structures in manoeuvring flight. In the present research, an attempt is made to provide a more feasible and practical approach to enhance the fidelity of a nonlinear simulation model by augmenting the rotor inflow components using the helicopter's roll and pitch rates and comparing the simulation results with flight test (FT) data for hover and low-speed flight condition. This is the first step in developing the process for application to predicting inflow dynamics and flight behaviour for larger manoeuvres, typical for example of certification tasks.

This paper is structured as follows: Section 2 presents a discussion on related research, followed by the aircraft modelling approach in FLIGHTLAB in Section 3. Section 4 describes the methodology of augmented inflows, with results shown in Section 5. The discussion and conclusions are presented in Sections 6 and 7, respectively.

2. RELATED RESEARCH

To improve the prediction of off-axis responses, different methods have been developed to incorporate the effect of wake distortions during manoeuvres. Rosen and Isser [5] used a curved helix model to describe the changes in the rotor wake geometry during pitching motion, such that the distance between the vortex filaments is reduced on the side of the disc moving downward, while increasing on the upward-moving side of the disc, resulting in a periodic variation of the induced velocity through the rotor disc. It was shown that the inclusion of these wake distortion effects leads to the correct off-axis response prediction for the AH-64 and UH-60 helicopters.

Keller [6] used an analytical method to include the effect of wake distortion due to the pitch and roll rates. The wake distortion was introduced to account for the variation of induced velocity component with translation speed and pitch rate. A simplified vortex analysis was used to obtain wake distortion coefficients for the UH-60 helicopter and it was shown that for certain values of wake distortion parameter, the lateral tip path plane tilt angle changes in sign, resulting in a significant effect on the off-axis response.

Pitt and Peters [4] used potential flow theory to include the contribution from the wake-skew angle to obtain closed-form solutions for the influence coefficient matrix. Peters and He [10] later generalised the Pitt and Peters model, and thereafter several variants of Peters–He's finite-state dynamic wake model have been proposed [11-14] to include the wake distortion effects.

Prasad et al. [15] used free-wake analysis to approximate the time-dependent nature of the wake during manoeuvring flight using first-order model representations and augmented the dynamic inflow model with additional states for wake-skew and wake-curvature. Zhao et al. [12] used vortex tube analysis to develop a dynamic wake distortion model, expressed as a set of ordinary differential equations, and extracted the corresponding non-dimensional time constants for the wake distortion parameters including wake-skew, wake-spacing and wake-curvature. The authors of [12] successfully augmented the Pitt and Peters dynamic inflow model with additional states for the wake distortion parameters and presented validation results for the UH-60 helicopter in hover.

Krothapalli et al. [13] used the wake-curvature computed using the body angular rates and blade flapping rate for enhancing the inflows. Goulos [16] and Zhao [17] worked to improve the cross-coupled responses in forward flight conditions on Bo105 and UH-60 helicopters, respectively. It was demonstrated that the rotor wake-curvature and wake-skew are coupled in forward flight conditions, and the inclusion of this behaviour in the dynamic inflow model improved the correlation between simulation and FT.

In Refs. [8,9] it was shown that, for the Bo105, the off-axis pitch response from a lateral cyclic input was significantly improved by adding two linear terms in the dynamic inflow equation as a function of aircraft pitch and roll rates. Researchers at the German Aerospace Center [18,19], used a similar approach with added effects from the lateral and longitudinal flapping rates, and the results were presented for Bo105 helicopter in hover, showing significant improvements in the off-axis pitch response from the lateral input.

Computational studies using free-wake models have also been performed to investigate the behaviour of rotor wake in transient manoeuvres [20], to show the complex nature of rotor wake. It was demonstrated that during a turn manoeuvre, the tip vortices bundle together near the tip and even cross the rotor plane as it extends from the retreating side to the advancing side of the rotor. The free vortex model offers a solution for predicting the complicated rotor wake variation; however the associated high computational cost is one of the biggest hurdles to

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use these methods for rotorcraft in manoeuvring flights. Regarding the development of simulation models, He et. al. [14] enhanced the Peters-He finite-state-inflow (FSI) model by including the effect of MWD on the rotor inflow dynamics, and interference effects of the rotor wake, particularly on the empennage of the helicopter. These enhancements were integrated into the real-time version of the simulation environment, FLIGHTLAB [21], to show an improved correlation for the off-axis response for the UH-60 helicopter.

Most of the publications regarding rotorcraft inflow models have been based on specific rotorcraft configurations, like UH-60, Bo105, AH-60 etc. Using these modelling configurations tailored to another rotorcraft configuration, e.g. the Bell 412, demands prerequisites of a high level of expertise and a profound understanding of rotor aerodynamics. Here, we present a new and feasible approach to compensate for the wake distortion through a proposed augmented inflow model, in which we directly augment the inflow components obtained as the solution of the dynamic wake equations, making it feasible to implement for any helicopter configuration.

3. AIRCRAFT MODELLING

3.1. Flight test data

FT data used in this work were obtained from the National Research Council of Canada's research Bell 412 (B412) Advanced Systems Research Aircraft (ASRA) as part of collaborative research on simulation fidelity [22]. ASRA is specially configured with on-board research equipment for the development and testing of advanced flight control systems and modern cockpit technologies. Specialized research equipment installed in the Bell 412 are a fly-by-wire system, force-feel system, and data acquisition system with graphical display capability.

The flight test data were collected as part of the flight test campaigns performed on the ASRA in 2004–6 and 2009–11 to support control law design (Ref. [23]) and simulation fidelity research (Refs. [24-27]) respectively at Liverpool. This paper focuses on the off-axis responses of the bare-airframe (i.e. SCAS off) rotorcraft using the lateral and longitudinal inputs in hover, consisting primarily of 2311 inputs. The selection of the data is based on the quality of the open-loop response, minimal off-axis inputs and the quality of the trim condition prior to the input being applied.

3.2. Simulation model

The baseline simulation model is the F-B412 [28], developed using the multi-body-dynamic modelling tools in the comprehensive simulation environment, FLIGHTLAB [21]. The F-B412 features a blade-element main rotor with non-linear aerodynamics and a Bailey tail rotor. The hingeless rotor is represented by rigid blades with hinge-offset-spring analogues for flap and lag dynamics. The fuselage and empennage aerodynamic forces and moments are derived from non-linear look-up tables. The Peters-He, three degree-of-freedom (3DoF), FSI [29] is used for the modelling of dynamic inflow. The extension of the FSI model to MWD was achieved in stages and was integrated into the real-time version of the simulation environment, FLIGHTLAB includes lookup tables populated using a prescribed vortex-wake model.

4. METHODOLOGY DESCRIPTION

Dynamic inflow models are used to capture, in an approximate manner, the three-dimensional effects of the flow through, and in the wake of, the rotor. The early work of Pitt and Peters [4] used a general formulation of the 3DoF dynamic inflow model to relate the inflows, λ's, with aerodynamic loadings, Cs, as

$$[M]\begin{bmatrix}\dot{\lambda}_0\\ \dot{\lambda}_{1s}\\ \dot{\lambda}_{1c}\end{bmatrix} + \bar{V}[L]^{-1}\begin{bmatrix}\lambda_0\\ \lambda_{1s}\\ \lambda_{1c}\end{bmatrix} = \begin{bmatrix}C_T\\ C_L\\ C_M\end{bmatrix} \qquad (1)$$

where C_T, C_L, C_M are coefficients of aerodynamic thrust and roll and pitch moment perturbations, $[M]$ and $[L]$ are the (apparent) mass, and influence coefficient matrices, respectively; λ_0, λ_{1s} and λ_{1c} are the values of the uniform (v_0), lateral (v_{1s}) and longitudinal (v_{1c}) variations of inflows normalised by rotor tip speed in hover (ΩR), where Ω is the main rotor speed and R is the main rotor radius. It was assumed that the inflows are related to aerodynamic loads in a first-order form (see eqn. (1)), developed as a closed-form solution for the mass matrix, M and influence matrix, L as a function of wake-skew angle, χ, appearing explicitly in the wake-skew parameter, as $X = \tan(\chi/2)$.

$$[M] = \begin{bmatrix}\frac{8}{3\pi} & 0 & 0\\ 0 & \frac{16}{45\pi} & 0\\ 0 & 0 & \frac{16}{45\pi}\end{bmatrix}$$

$$[L] = \begin{bmatrix}\frac{1}{2} & 0 & -\frac{15\pi}{64}X\\ 0 & 2(1+X^2) & 0\\ \frac{15\pi}{64}X & 0 & 2(1-X^2)\end{bmatrix}$$

In the current work, the Peters-He 3DoF FSI model [29] is used to predict the rotor inflow and approximate additional manoeuvre wake and wake-skew effects, by augmenting the inflow components, in the form:

$$\lambda_{1cA} = \lambda_{1c} + K_{pc}\bar{p} + K_{qc}\bar{q} + K_{uc}\bar{u} + K_{vc}\bar{v} \qquad (2)$$

$$\lambda_{1s} \;= \lambda_{1s} + K_{ps}\bar{p} + K_{qs}\bar{q} + K_{us}\bar{u} + K_{vs}\bar{v} \qquad (3)$$

where, $\bar{p}$, $\bar{q}$ are roll and pitch rates normalised by the Ω; $\bar{u}$ and $\bar{v}$ the surge and sway velocities normalized by the rotor tip speed in hover (ΩR). In the methodology of augmented inflows, the values of the augmentation coefficients are computed using an optimisation process that minimises the differences in the on-axis and off-axis rate and velocity responses between simulation and FT data in both lateral and longitudinal motions. Figure 1 presents a schematic of the methodology for augmenting the rotor inflows in the F-B412. The optimisation is performed within FLIGHTLAB simulation environment to match the flight simulation (FS) response as close as possible to the FT data, computed using the cost function, C_f as

$$C_f = \sqrt{\sum_{i=1}^{4} w_i \times (FT_i - FS_i)} \qquad (4)$$

where, $i = 1, 2, 3, 4$ represents the aircraft roll rate, pitch rate, sway and surge velocities respectively, and w_i is the weighting factor for each body state. For this initial study, the values $w_1 = w_2 = 1$ and $w_3 = w_4 = 0.1$ are used, as the numerical values of the normalised translational velocities are typically an order of magnitude higher than the normalised body rates.

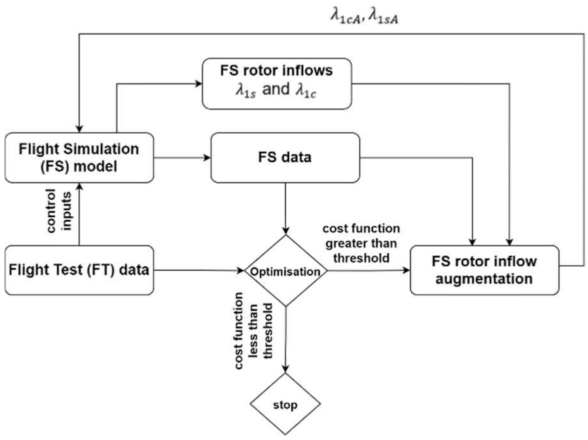
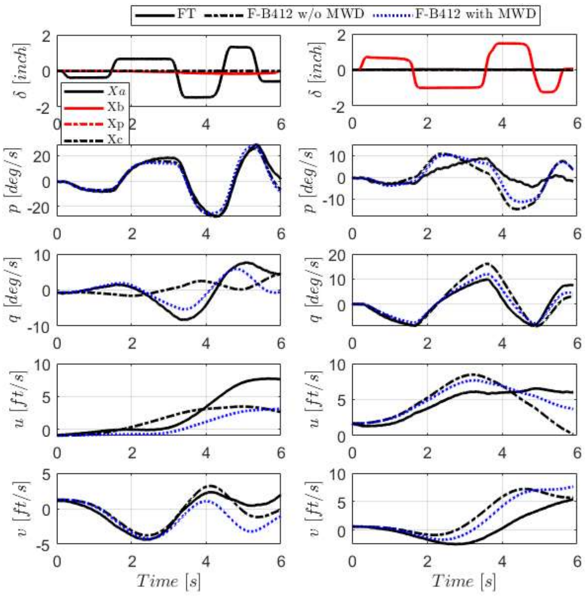


Figure 1 Methodology of augmented inflows for flight simulation mode

5. RESULTS

5.1. Augmented Inflows

The control inputs from the FT are used to drive the nonlinear simulation model, F-B412 with and without the MWD, for the lateral and longitudinal cyclic control inputs in hover (Figure 2). The on-axis response in both cases show reasonable agreement with the FT; the first attitude rate peak is well captured with some deviations noted near the second peak. The off-axis responses are poor in both cases without MWD; pitch from roll is of opposite sign initially and the roll response from pitch is much stronger in the flight simulation, noticeably at the second peak. The FLIGHTLAB MWD model captures the first peak of the pitch response during the roll input, but also departs from FT near the second and third roll peaks. The predicted (coupled) surge and sway velocities also deviate from the FT data after a few seconds. The translational velocities are strongly related to the attitude excursions of course but also drive the wake skewing, leading to further coupled rotational motion.



(a) (b)

Figure 2 Comparison of FT responses with the F-B412 with and w/o MWD, (a) lateral cyclic, (b) longitudinal cyclic.

The methodology of augmented inflows as described in Section 4 is used to obtain the augmentation coefficients using the FT data from the ASRA. In addition, an investigation was performed to capture the MWD effect using a reduced-order model to substantiate the contributions from the fuselage roll and pitch rates, with the simpler model structure as

$$\lambda_{1cA} = \lambda_{1c} + K_{pc}\bar{p} + K_{qc}\bar{q} \qquad (4)$$

$$\lambda_{1sA} = \lambda_{1s} + K_{ps}\bar{p} + K_{qs}\bar{q} \qquad (5)$$

The identification of augmentation coefficients using the reduced model structure is performed using the same optimisation process used to obtain the results, as described in Figure 1. These augmentation coefficients are used to enhance the components of rotor inflows v_{1s} and v_{1c}, which in turn contribute to the improvement in the off-axis pitch rate from the lateral cyclic input (Figure 3), and roll rate from the longitudinal cyclic input (Figure 4). The results for the full and reduced-order model structure are shown in Table 1.

Table 1 Augmentation coefficients for F-B412 in hover using reduced and full model structures

Augmentation coefficients	Reduced model structure	Full model structure
$\boldsymbol{K_{ps}}$	1.69	1.09
$\boldsymbol{K_{qs}}$	1.12	0.98
$\boldsymbol{K_{pc}}$	-0.06	-0.05
$\boldsymbol{K_{qc}}$	0.36	0.49
$\boldsymbol{K_{us}}$	-	0.12
$\boldsymbol{K_{vs}}$	-	-0.33
$\boldsymbol{K_{uc}}$	-	-0.17
$\boldsymbol{K_{vc}}$	-	0.16

6. DISCUSSION

The methodology of augmented inflows deals with one of the many possible causes of incorrect cross-couplings at hover, i.e. MWD-like behaviour. The results presented for hover showed that the cross-coupled responses of roll from pitch and pitch from roll can be substantially improved with additional non-uniform inflow components proportional to fuselage roll (p), pitch (q) rates, surge (u) and sway (v) velocities. The contributions of individual components to the inflows (v_{1s} and v_{1c}) for the full model structure are shown in Figure 5.

For the X_a input (Figure 3), the relatively small surge and sway velocity perturbations result in the on-axis v_{1s} being dominated by the roll rate and off-axis v_{1c} dominated by pitch rate, or MWD-like effects. The full-order augmentation serves to give a close correlation with the translational velocities. For the X_b input (Figure 4), the much larger off-axis v_{1s} improves the on-axis q response at the second peak. While the off-axis p response correlation is improved with the full and reduced-order augmentation, the v_{1c} perturbations are clearly insufficient to give a close match, particularly between two and four seconds.

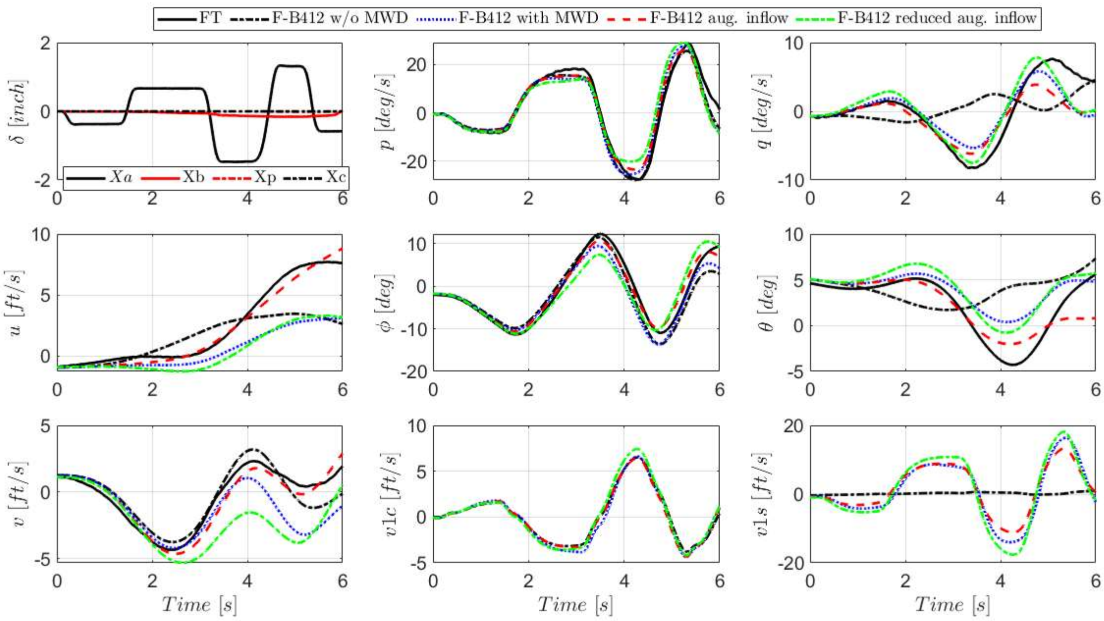


Figure 3 Comparison of FT responses with F-B412 model with augmented inflows for a lateral cyclic input in hover

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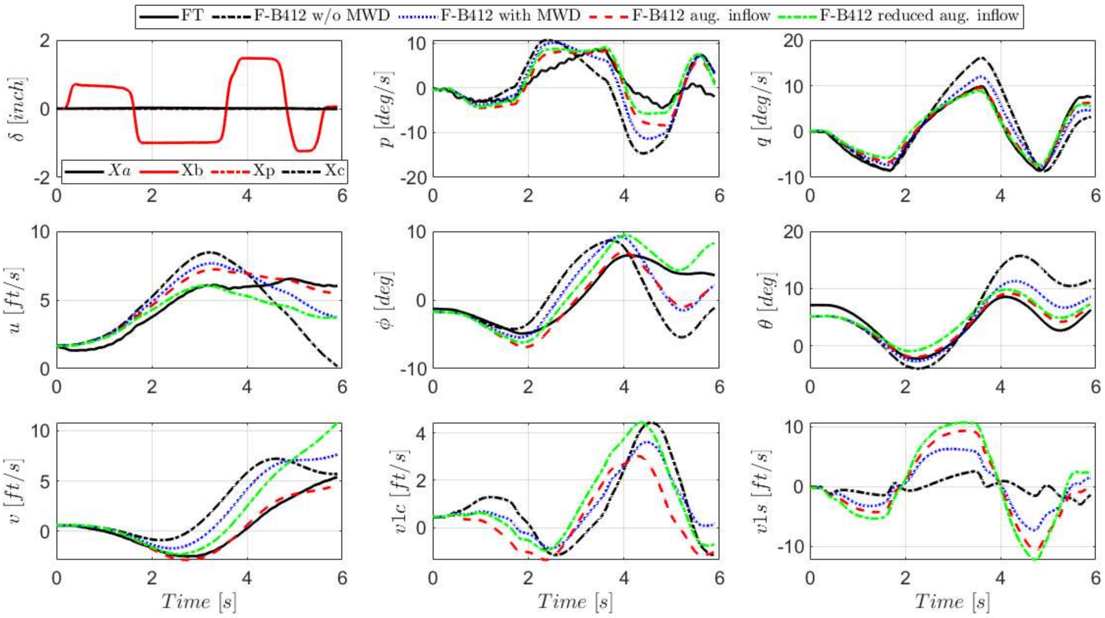
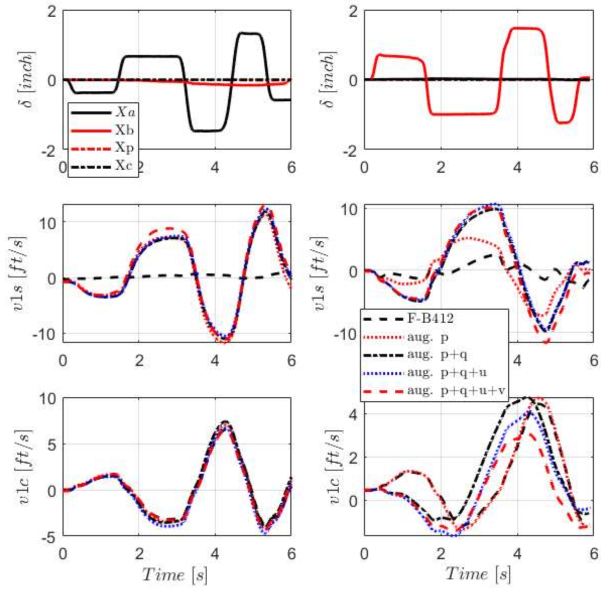


Figure 4 Comparison of FT responses with F-B412 model with augmented inflows for a longitudinal cyclic input in hover



(a) (b)

Figure 5 Contribution of individual components to the rotor inflows using the full scale augmented inflow model, (a) lateral cyclic input, (b) longitudinal cyclic input.

Table 1 shows that the values of augmentation coefficients in the reduced model structure (eqns. (4), (5)), generally have higher values compared to their values in the full-order model structure (eqns. (2), (3)). This suggests that it is not only the wake curvature that contributes towards the correction of the inflows. The inclusion of body velocities in the model structure changes the required inflow augmentation due to the rotor wake curvature. Figure 5 confirms the dominant impact of roll rate *p* on both non-uniform inflow components for the response to the X_a input. The combined *p* and *q* effects capture most of the v_{1s} inflow in the response to the X_b input, while the sway velocity component appears to lag the v_{1c} peak value relative to the *p* and *q* effects. The greater complexity of the inflow perturbations for responses to the X_b control is surprising and certainly warrants further investigation.

The results obtained in this work reinforce the benefits of using the augmentation methodology for modifying the rotor inflows using the helicopter's motion parameters, showing a close match between the FT and FS results. It is acknowledged that changing the inflows will also influence the rotor wake interference on aerodynamic surfaces. Furthermore, as the translational velocities increase, the impact of rotor wake interference is likely to increase, and extensions of the approach presented in this paper to account for these effects is essential; this is the subject of the ongoing research involving flight testing on the ASRA.

7. CONCLUSIONS

This paper reports progress in the development of a new approach to the exploration of rotorcraft simulation fidelity using augmented rotor inflow dynamics. The approach has been applied to predicting responses from a hovering flight condition. In the present investigation, flight test data have been used to examine the fidelity of a nonlinear FLIGHTLAB model of a Bell 412 helicopter. From the analysis undertaken, the two main conclusions are:

1) The modelling approach of augmenting the rotor inflows using body rates (*p, q*) and velocities (*u,*

v) has proved effective in capturing the off-axis responses following control inputs, confirmed by the resulting matches with flight test data.

2) Investigation of the reduced model structure has demonstrated how the changes in body translational velocities during the manoeuvre contribute to minor changes in rotor inflow.

The preliminary results are encouraging and the ongoing research is addressing the creation of simplified inflow models for predicting behaviour for larger velocity excursions during mission task elements.

8. ACKNOWLEDGEMENTS

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Rotorcraft simulation fidelity improvements through augmented rotor inflow

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